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Burnout in Turbulent Flow — A Droplet Diffusion Model[1]

K. GOLDMANN

Nuclear Development Corporation
of America, White Plains, N. Y.
Assoc. Mem. ASME.

H. FIRSTENBERG

Nuclear Development Corporation
of America, White Plains, N. Y.

C. LOMBARDI

Centro Informazioni Studi
Esperienze, Milan, Italy. [redacted]

Two-phase flow regimes are reviewed briefly. A physical model, which is based on the concept that droplet diffusion through a steam boundary layer is the limiting mechanism for burnout in turbulent flow, is described. An equation is derived relating burnout to other parameters in fog flow. With simplifying assumptions, an order-of-magnitude agreement between analysis and experimental burnout data in fog flow is demonstrated.

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K. GOLDMANN

H. FIRSTENBERG

C. LOMBARDI

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Nomenclature

- $\bar{c}$ = average liquid droplet concentration, lb_m/cu ft
- c = liquid droplet concentration, lb_m/cu ft
- D = equivalent diameter, ft
- f = friction factor
- G_t = total mass flow rate, lb_m/hr-sq ft
- h_{fg} = latent heat of vaporization, Btu/lb_m
- k_g = film coefficient for mass transfer, fph
- $K_G \equiv k_g/u_g$ = dimensionless mass transfer coefficient
- $\dot{m}$ = liquid droplet mass current, lb_m/hr-sq ft
- Re = Reynolds number
- $s \equiv u_g/u_f$ = axial slip ratio
- Sc = Schmidt number
- u = average velocity at a section, fph
- x = average steam flow quality at a section, weight fraction
- Φ_{BO} = burnout heat flux, Btu/hr-sq ft
- μ = viscosity, lb_m/hr-ft

Subscripts

- f = liquid phase
- g = vapor or gas phase
- w = wall

INTRODUCTION

Burnout presents one of the principal limitations in the design of liquid or wet steam-cooled nuclear reactors, rocket nozzles, and other high-specific-power equipment. Because of this, the subject of burnout has received considerable attention during the past decade. The present state-of-the-art in the U. S. and abroad is well described in several reviews (1-6).[2] It is apparent from these publications that today's knowledge is not sufficient to predict burnout with the desired degree of accuracy.

Analytic methods for predicting burnout have utilized physical models which have generally been based on visual observations of pool boiling. These observations have led to methods which are tied to bubble dynamics or to the movement of liquid and vapor spikes in regular geometric cells. Since they are based on pool-boiling observations, it is not surprising that these analyses correlate pool-boiling data quite well. However, they fail for flowing systems.

It is suggested in the present paper that the controlling mechanism for burnout in flowing systems, particularly at high Reynolds numbers, is not to be found in bubble behavior but rather in the eddy diffusion-limited transport of liquid droplets through a steam boundary layer to the heated wall. This concept appears particularly attractive for fog flow, but may also be applicable to flowing low-quality steam and even subcooled liquid systems.

This concept grew out of an earlier one described by Cicchitt, et al (7). They postulated that the heat-transfer area is covered by a thin liquid layer which is continuously fed by water drops carried by the steam flow. During the preparation of the present paper our attention was called to theories by Vanderwater (8), Singh (9), and Fauske (10), who similarly proposed that burnout occurs when the liquid mass flow through an annular film and from diffusing droplets is insufficient to support the heat flux. Reynolds (11) proposes a correlating factor which is based on all the liquid being in an annular film at the wall.

In this paper, two-phase flow regimes are briefly reviewed, a burnout model is described, basic equations for burnout in fog flow are derived and a preliminary comparison is made between analysis and the results from burnout experiments in the fog-flow regime.

TWO-PHASE FLOW REGIMES

Much of the burnout data, needed for the design of nuclear reactors, has been obtained experimentally with high-pressure water in the quality region. It is instructive to attempt to visualize what the appearance of the two-phase mixture might be in this region.

The flow of two-phase mixtures has been observed by numerous investigators under isothermal conditions and has been summarized in References (5), (12) and (13). The observed two-phase flow regimes are well described by the names frequently applied to them; namely, annular, slug, dispersed, bubble, froth, and so on. There is no uniform agreement on terminology or even on the number and boundaries of regimes that do occur.

[2] Underlined numbers in parentheses designate References at end of paper.

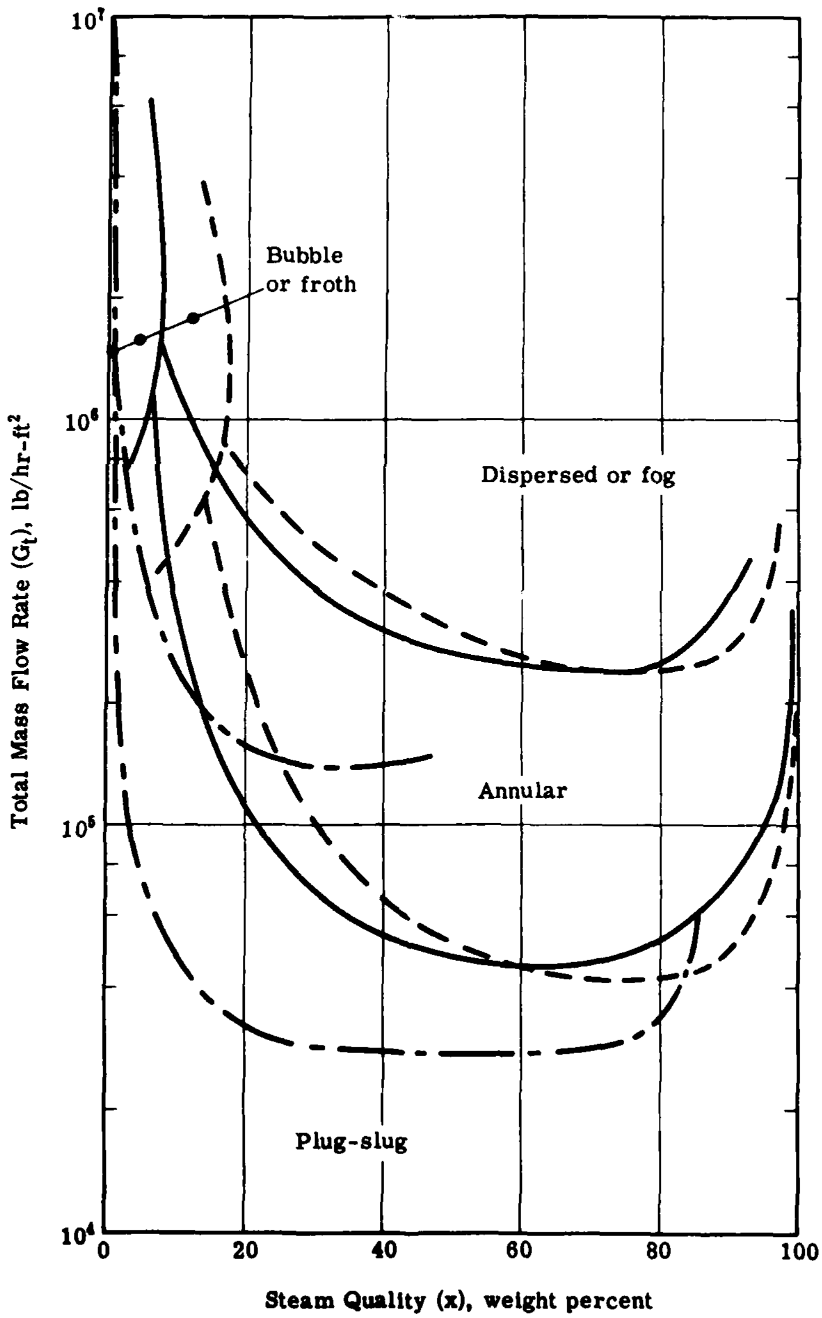

Fig. 1(a) Steam-water system flow pattern chart. — — — - 14.7 psia; ——— 800 psia; - - - - 1500 psia. (Based on reference 14)

One can nevertheless construct a flow-pattern chart for steam and liquid water, based, for instance, on Baker's plot (14), as shown in Fig.1. Keeping in mind that the boundaries between regimes shown as lines in Fig.1 are really not sharply defined and that heat addition in small channels will move the boundaries towards lower qualities and lower mass-flow rates, one can still reach certain over-all conclusions.

First, it will be noticed that at mass-flow rates larger than 500,000 lb/hr-sq ft, which are of interest to nuclear reactors and other high-velocity systems, and for which most of the experimental burnout data have been taken, the fluid is either in the bubble-froth or in the dispersed-fog flow regime. Bubble-froth flow, as shown in

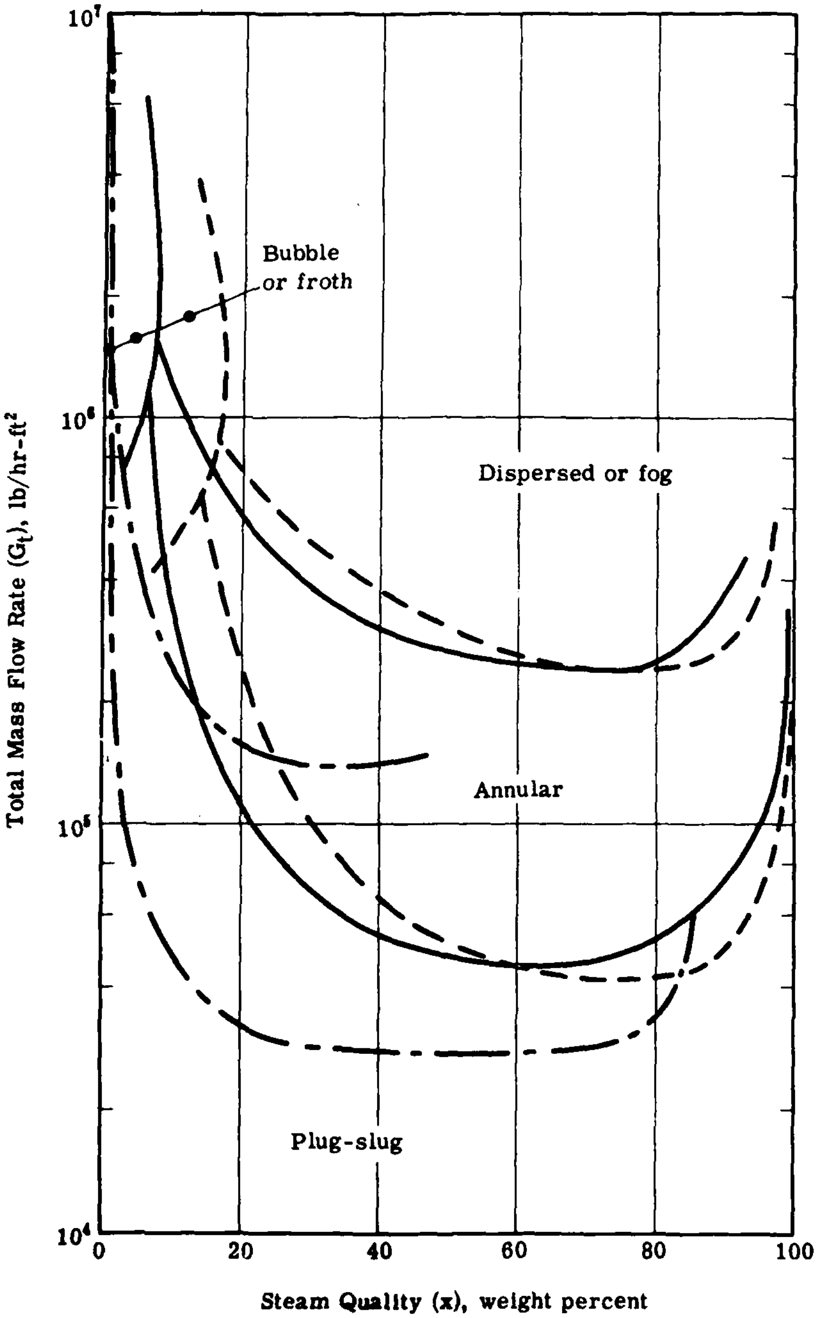

Fig. 1(b) Steam-water system flow pattern chart. — - — - 14.7 psia; —— 800 psia; ---- 15,000 psia. (Based on reference 14)

Fig.1, occurs at steam qualities of less than approximately 10 per cent depending on pressure and probably on heat flux. As the name indicates, in this regime, the fluid is essentially a liquid containing vapor bubbles. At steam qualities between 10 and 100 per cent and high velocities, the fluid is essentially a fog; i.e., steam with a dispersion of liquid droplets.

In the fog-flow regime most of the liquid is carried in droplet form by the steam, although under isothermal conditions a thin liquid film can be observed at the wall. Since there are no thick layers or slugs of liquid, it is difficult to visualize the growth and movement of bubbles in fog flow, and one is forced to abandon for this regime burnout models which are based on bub-

ble dynamics. A droplet diffusion model is proposed in its stead as follows:

DESCRIPTION OF BURNOUT MODEL

Fog Flow

In fog flow, liquid droplets are more or less uniformly dispersed in the high-velocity steam. Under high heat fluxes, the liquid which is cooling the wall evaporates and must be replenished by droplets from the main stream if burnout is to be avoided. It is proposed that this replenishing is accomplished by eddy diffusion of droplets. The amount of liquid which can be transported to the wall is limited by this turbulent diffusion process, and one may postulate that, to a first approximation, burnout will occur when the heat flux becomes greater than that needed for the complete evaporation of all liquid droplets which diffuse to the wall. At any rate, this heat flux represents an upper limit for burnout.

In this model, the vaporization of droplets at the heated wall provides a diffusion sink and thus establishes a concentration gradient for a net current of droplets to flow from the main stream to the wall. A similar diffusion process has been investigated by Alexander and Coldren (15). They performed a series of experiments to elucidate the mechanism and to measure typical rates of deposition, on the walls of a straight duct, of small water droplets suspended in a turbulent air stream. In their experiments, the thin liquid film at the wall acted as a diffusion sink, and the major resistance to droplet transfer from the air stream to the duct wall resided in a relatively thin layer of air adjacent to the wall.

From experiments like these and further analyses, it should be possible to deduce the droplet-diffusion rates as functions of pertinent parameters. By assuming that these diffusion rates are controlling, functional relations between burnout and these parameters can then be established, which in turn would permit the reliable prediction of burnout heat fluxes for conditions of engineering interest. Some initial steps for doing this are indicated later in sections dealing with the development of basic equations and comparison of data. It should be noted that no assumptions need to be made about the evaporating process itself, since liquid diffusion rates are assumed to be controlling.

Although knowledge of the evaporating process is not required for the development of the equations, it is interesting to speculate as to what this process may be. We presently believe that droplets reaching the wall evaporate there without forming liquid films which are thick enough to support bubble growth. The resulting vapor flows away from the wall into the main stream, thus opposing the movement of droplets towards the wall. In cases of so-called "slow burnouts" (16) a considerable fraction of droplets may never reach the wall at all but may evaporate in the slightly superheated steam boundary layer.

Other Flows

One may speculate that the diffusion of droplets, rather than the growth of bubbles, is also controlling for burnout in low quality and even in subcooled, turbulent flows. The basis for this hypothesis is that near burnout fluxes there is a layer of vapor near the wall and the "boundary" layer is in fog flow. Again no bubbles can really grow at the wall. Questions related to the thickness of the fog layer, the effective liquid concentration in the main stream and radial sprays need to be answered before quantitative analyses could be undertaken to predict burnout fluxes based on a droplet-diffusion model for these flows.

DEVELOPMENT OF EQUATIONS FOR FOG FLOW

The problem of mass transfer of liquid droplets from a turbulent stream to a solid boundary may be viewed mathematically in a manner analogous to the treatment of turbulent momentum exchange and heat transfer. Implicit in such a mathematical description is the assumption that the primary resistance to mass diffusion occurs in a layer of low turbulence adjacent to the solid boundary.

One may define a film coefficient for mass transfer by the equation

$$k_g \equiv \dot{m}_w/(\bar{c} - c_w) \tag{1}$$

If the solid boundary under consideration is a heating surface, then the potential heat-removal capacity of the system can be related to the liquid-droplet mass current by a heat balance, in line with the previously described model. Burnout may be assumed to occur when the surface heat flux is equal to the potential heat-removal capacity of the diffusing liquid. Combining these concepts we obtain the basic correlation relating burnout to the diffusion properties of the system, or

$$\Phi_{BO} = k_g h_{fg}(\bar{c} - c_w) \tag{2}$$

With the assumption that all the liquid reaching the wall is evaporated at the condition of burnout, the wall becomes a diffusion sink and $c_w = 0$. Thus, Equation (2) becomes

$$\Phi_{BO} = k_g h_{fg}\bar{c} \tag{3}$$

The average liquid-droplet concentration in the main stream can be approximated by

$$\bar{c} \simeq (1 - x)G_t/u_f \tag{4}$$

This assumes that the droplet concentration is essentially uniform over most of the cross section and that the concentration gradient for diffusion exists in a relatively thin film near the wall. Combining Equations (3) and (4) and multiplying the right-hand side of the resulting equation by u_g/u_g we obtain

$$\Phi_{BO} = \frac{k_g}{u_g}\frac{u_g}{u_f}(1 - x)G_t h_{fg} \tag{5}$$

or

$$\Phi_{BO} = K_G s(1 - x)G_t h_{fg} \tag{6}$$

This is the basic equation for predicting burnout. It cannot be readily used until more information is available on mass-transfer coefficients and slip. As will be shown later, the principal uncertainties in estimating mass transfer coefficients lie in a lack of knowledge of eddy slip. Thus two types of slip are of concern; axial slip and eddy slip.

Axial Slip

In any flowing system in which liquid droplets are introduced into a high-velocity vapor stream, the droplets will experience acceleration, or deceleration, until their velocity approaches that of the carrier fluid. In a fog-flow heat-transfer system, the carrier fluid is continuously accelerating. Thus, unless the acceleration of the carrier fluid is occurring at an extremely slow rate the droplets will always tend to lag the carrier fluid; i.e., axial slip will persist. Axial slip has been measured at a number of installations, but the available data are too fragmentary to be of practical use for present purposes.. Levy (17) reviews these data and proposes a model for the prediction of slip. For use in Equation (6) we suggest that slip is a function of a number of parameters such as

$$s = s\left(P, G, x, \frac{dx}{dL}, L, D\right) \tag{7}$$

and that considerably more work needs to be done to elucidate this function. Preliminary studies indicate that axial slip is near unity in fog flow.

Eddy Slip

The eddy motion of the carrier fluid has been postulated as the mechanism which transports liquid droplets from one point in the stream to another. The droplet transport to the wall could be calculated from an analogy between mass and momentum transfer in turbulent streams (18, 19). This analogy assumes that the diffusing material can follow the eddy motion of the carrier fluid exactly; that is, eddy diffusivities for mass and momentum transfer are equal. However, in the eddy diffusion of liquid droplets, the greater inertia of the droplets prevents them from following the carrier fluid motion exactly. This "eddy slip" results in lower values for mass eddy diffusivities and, therefore, mass transfer coefficients, than would be obtained from the analogy.

An estimate of this effect was made by Longwell and Weiss (20) for the eddy slip of a 45 μ diameter kerosene droplet in atmospheric air flowing through a 6-in. duct at a velocity of 300 fps. For these conditions, they found the ratio of the eddy diffusivities of mass-to-momentum transfer to be 0.35.

COMPARISON OF ANALYSIS AND EXPERIMENTS IN FOG FLOW

Although we do not know the exact values for axial and eddy slips, some preliminary comparison of analysis and experiments can be made to indicate that the proposed model does show promise.

For this purpose, one may make the assumption that the axial slip ratio is equal to one and calculate mass transfer coefficients from burnout data using Equation (6)

$$[K_G]_{s=1} = \left[\frac{\Phi_{BO}}{(1 - x)G_t h_{fg}}\right]_{s=1} \tag{8}$$

Following the analogy between mass and momentum transfer, Lin, et al (19) have shown that

$$K_G \equiv \frac{k_g}{u_g} = F(Re, Sc) \tag{9}$$

and for cases in which the Schmidt number is near unity, the analysis reduces to

$$K_G \doteq \frac{k_g}{u_g} = \frac{f}{2} = F(Re) \tag{10}$$

Thus one may plot mass transfer coefficients and friction factors against Reynolds number to test the validity of the postulated burnout model by observing the spread of data, keeping in mind that the spread may be considerable because of the oversimplifying assumptions of axial slip ratios, eddy slip ratios and Schmidt number equal to 1.

Fig.2 serves this purpose. It shows mass transfer coefficients, as calculated from Equation (8), plotted against Reynolds number for all experimental burnout data which have been available to us in the steam quality range of 20 to 100 per cent and pressure range of 500 to 1500 psia. The Reynolds numbers have been formed by the arbitrary

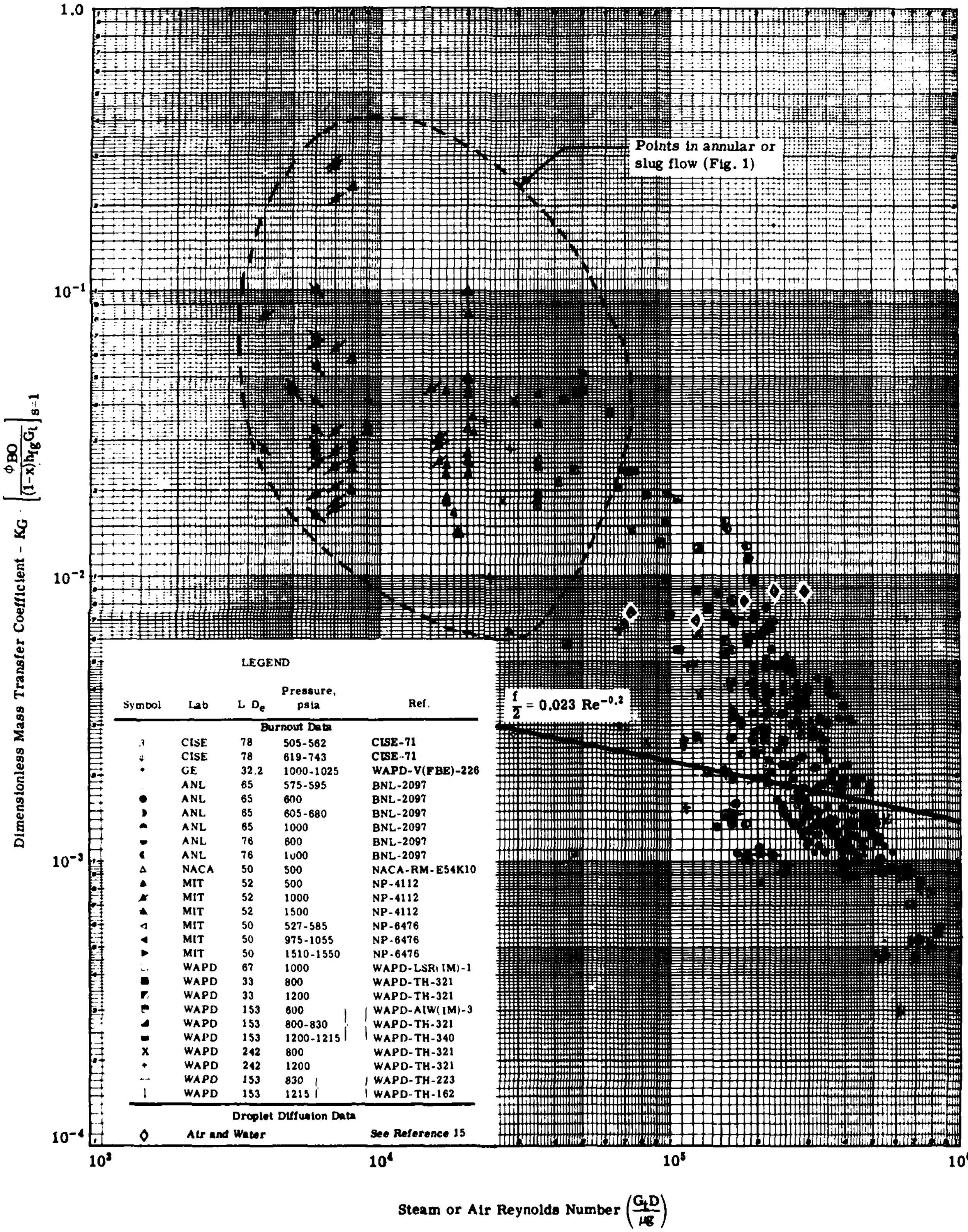

Fig. 2(a) Dimensionless mass transfer coefficient versus Reynolds number

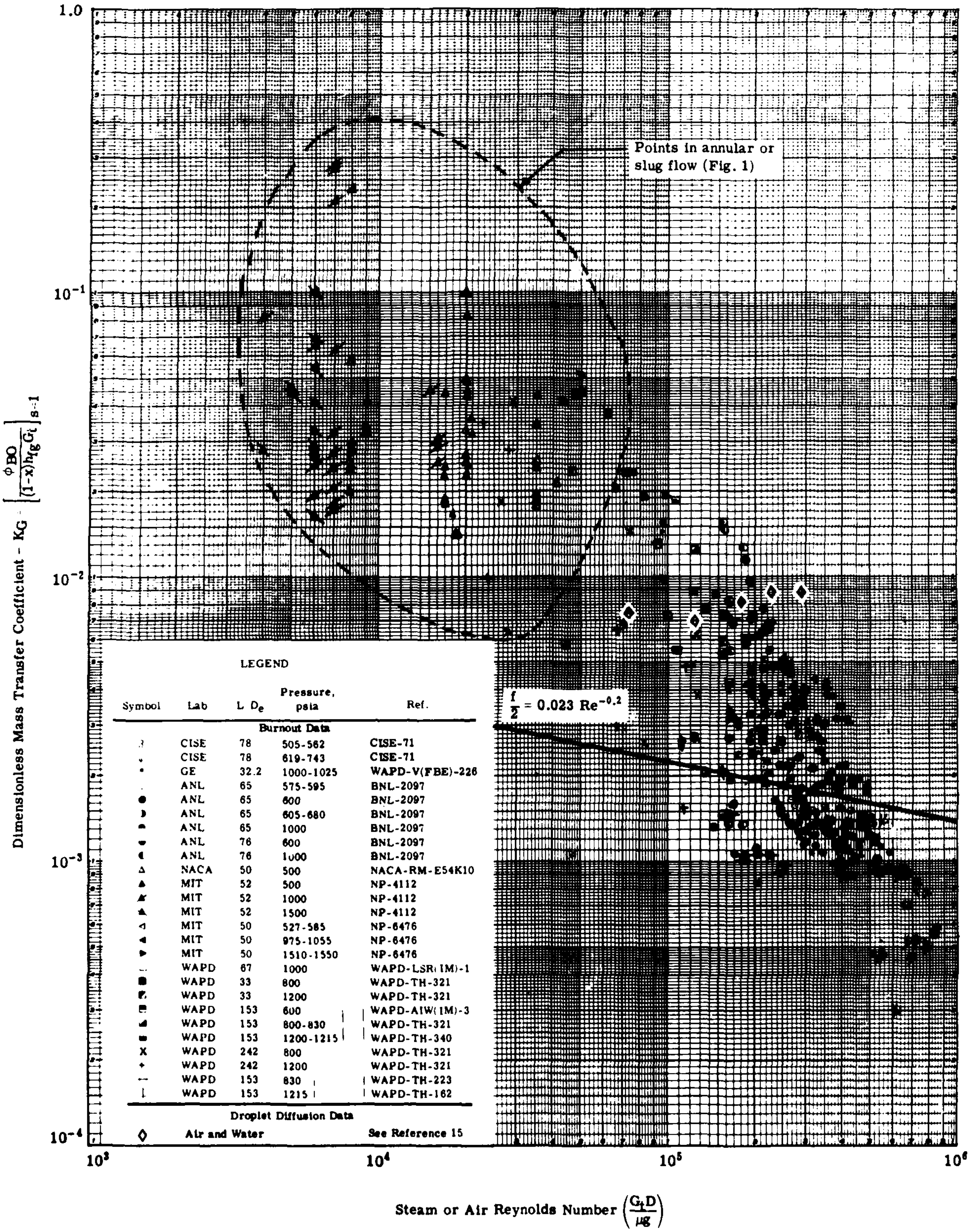

Fig. 2(b) Dimensionless mass transfer coefficient versus Reynolds number

use of saturated steam values for viscosities and total steam and liquid flows for calculation mass velocities.

Also shown in Fig.2 are the droplet mass transfer coefficients measured directly by Alexander and Coldren and the friction factor line, $f/2 = 0.023/Re^{0.2}$. In view of the oversimplifying assumptions, the order of magnitude agreement between mass transfer coefficients and $f/2$ is remarkable.

As indicated in Fig.2, some of the burnout data had been taken in the annular and slug flow regimes. Their spread is large because the simplifying assumptions which are more nearly applicable to fog flow are not valid in these flow regimes.

The spread of the fog-flow burnout data is also considerable, but can be explained qualitatively by slip ratio considerations. It is hoped that further work on gaining insight into turbulence levels of two-phase mixtures, droplet size distributions and droplet diffusion processes will provide functions for mass transfer coefficients and slip ratios which can then be used to predict burnout heat fluxes with the proposed model.

CONCLUSIONS

1 It is proposed that droplet diffusion through a steam boundary layer towards the heated wall is the controlling mechanism for burnout in fog flow.

2 It is suggested that the same mechanism may be controlling for burnout in high-velocity, low-quality and even subcooled flow systems.

3 An equation, relating burnout in fog flow to variables describing the droplet diffusion process, has been developed.

4 The usefulness of this equation is presently limited because data for certain quantities such as axial slip and droplet mass transfer coefficients are not available.

5 Applying the equation, with the axial slip ratio equal to one, to experimental burnout data in fog flow, results in an order-of-magnitude agreement between calculated mass transfer coefficients and single-phase friction factors.

6 It is recommended that future investigations of burnout in turbulent flows concentrate on gaining insight into processes related to the diffusion of droplets and their evaporation at heated walls.

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